Sand Ripple Dynamics on the Inner Shelf

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LONG-TERM GOALS

The goals of this work are to develop better understanding and predictive capability for the development and evolution of sand ripples in coastal oceans.

OBJECTIVES

We are developing two coupled hydrodynamic – sediment transport, live-bed models for sand ripple evolution. These models simulate the response of the sea-bed under oscillatory and wave-current induced boundary layer flows.

APPROACH

The work involves theoretical development, numerical computations, and comparison with laboratory and field measurements. The first coupled two-phase flow model utilizes a mixture approach, where the properties of the mixture are a strong function of the sediment concentration. In the solid bed, in the regime of enduring contact between sediment particles, the bed is rigid and resists a normal stress. In the interface region, between the sediment and water, where the concentration decreases, the mixture density and viscosity are dependent on the local concentration. The second model simulates the hydrodynamics directly, and uses standard relationships (Meyer-Peter, 1948; Bailard, 1981; Bagnold, 1966; etc.) for bed-load and suspended load transport based on the wall shear stress above the sand ripple. Then, by calculating the divergence of the local sediment transport, the bed height is integrated forward in time.

WORK COMPLETED

In the first model, we assume that a system containing sediment particles can be approximated as a mixture having variable density and viscosity that depend on the local sediment concentration and fluid-particle and particle-particle interactions are expressed through the mixture viscosity and a stress-induced diffusion term. In this approach, there are five governing equations that describe the flow field – the mixture continuity and momentum equations and a species continuity equation for the sediment. The control volume approach on a three-dimensional staggered grid is used to solve the

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equations numerically. The turbulent dynamics of an initially stationary densely packed sand layer (60% by volume sand) in the approximate shape of a wave-orbital sand ripple, is coupled to a sinusoidally oscillating flow. The model does a reasonable job of predicting concentration profiles and sea bed evolution over a few periods of wave oscillations. Both the model and the experimental data show that a significant amount of sand is entrained during the acceleration phases of the wave cycle. This entrained sand then falls back to the bed during the deceleration phase of the wave cycle and contributes to growing the sand ripple. It also appears that bed-load transport is the dominant mechanism for ripple formation, and we have shown that ripples can form for situations where suspended load is minimal. The equations governing sediment transport are the mixture continuity and momentum equations and a species continuity equation for the sediment. Development of these equations begins with the individual continuity equations for the fluid and sediment. The fluid and sediment continuity equations are $\frac{\partial(1-C)\rho_f}{\partial t}+\frac{\partial(1-C)\rho_f u_{fj}}{\partial x_j}=0$ [1] and $\frac{\partial C\rho_s}{\partial t}+\frac{\partial C\rho_s u_{sj}}{\partial x_j}=0$, [2]

where C is the sediment volume concentration, ρ_f and ρ_s are the fluid and sediment densities, and u_f and u_s are the fluid and sediment velocities. Adding Eqs. [1] and [2] and defining mixture density and momentum as $\rho=(1-C)\rho_f+C\rho_s$ [3] and $\rho u_j=(1-C)\rho_f u_{fj}+C\rho_s u_{sj}$ [4], where ρ is the mixture density and u is the mixture velocity, gives the mixture continuity equation, $\frac{\partial\rho}{\partial t}+\frac{\partial\rho u_j}{\partial x_j}=0$.[5]

Correspondingly, the mixture momentum equation is $\frac{\partial\rho u_i}{\partial t}+\frac{\partial\rho u_i u_j}{\partial x_j}=-\frac{\partial P}{\partial x_i}+\frac{\partial\tau_{ji}}{\partial x_j}+F\delta_{i1}-\rho g\delta_{i3}$, [6]

where P is pressure, τ_{ji} is the stress tensor, F is the external driving forcing, and g is the gravitational constant (Drew, 1983; Bird et al, 1960). Studies (Bagnold, 1954; Hunt, et al 2002; Acrivos, 1995) have determined that fluid-sediment mixtures may follow Newton's law of viscosity so that τ_{ji} is given by $\tau_{ji}=\mu\left[\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\frac{\partial u_k}{\partial x_k}\right]$, [7] where μ is the mixture viscosity (Bird, et al, 1960). Leighton and Acrivos (1986) have shown that fluid-sediment viscosities can be expressed as a function of sediment concentration using $\mu=\mu_f\left[\frac{1.5CC_p}{C_p-C}\right]^2$, [8] where μ_f is the fluid viscosity and C_p is the maximum packing concentration (e.g., $C_p = 0.64$ for random close packing). The flow is driven by an external oscillating force (F), which is given by $F=\rho_f U_0\frac{2\pi}{\lambda}\cos\left(\frac{2\pi}{\lambda}t\right)$, [9] where U_0 and λ are the amplitude and frequency of oscillation. The sediment continuity equation is $\frac{\partial C}{\partial t}+\frac{\partial Cu_j}{\partial x_j}=-\frac{\partial CW_t}{\partial z}+\frac{\partial N_j}{\partial x_j}$, [10]

where Wt is the settling velocity and N is the "diffusive" flux of sediment (Phillips, 1992; Nir and Acrivos, 1990; Subia et al, 1998; Leighton and Acrivos, 1986). Richardson and Zaki (1954) showed that $W_t=W_{t0}(1-C)^q$ [11] can be used to calculate settling velocity as a function of sediment concentration, where W_{t0} is the settling velocity of a single particle in a clear fluid and q is an empirical constant that depends on the particle Reynolds number (Re_p). Re_p is defined as

$\mathrm{Re}_p = \dfrac{d\rho_f |W_{t0}|}{\mu_f}$, [12] where d is the particle diameter and $q = 4.35\,\mathrm{Re}_p^{-0.03}$ when $0.2 < \mathrm{Re}_p < 1$, [13]

$q = 4.35\,\mathrm{Re}_p^{-0.10}$ when $1 < \mathrm{Re}_p < 500$, [14] and $q = 2.39$ when $500 < \mathrm{Re}_p$ [15]. Numerous studies have been performed to try to understand the "diffusion" of sediment in moving fluids, with appropriate models proposed for the diffusive term in Eq. [10]. These studies have shown that sediment diffusion can depend on the collision frequency, the spatial variation of viscosity, and Brownian diffusion such that $N = N_c + N_\mu + N_B$, [16] where N_c is the flux due to collisions, N_μ is the flux due to viscosity variation, and N_B is the flux due to Brownian diffusion. The expression for sediment diffusion developed by Nir and Acrivos (1990) for sediment flow on inclined surfaces is used as a first approximation. Their expression accounts for the flux due to collisions only and follows a Fickian diffusion form with a variable diffusion coefficient that is a function of particle size, concentration, and mixture stresses so that $N_j = D\dfrac{\partial C}{\partial x_j}$, [17] where $D = d^2\beta(C)\left|\dfrac{\partial u_j}{\partial x_i}\right|$. [18] β(C) is a dimensionless diffusion coefficient that was determined empirically by Leighton & Acrivos (1986) and is given by $\beta(C) = \dfrac{1}{3}C^2\left(1+\dfrac{1}{2}e^{8.8C}\right)$ [19]. Using d, C_m (maximum sediment concentration), ρ_f, μ_f, $|W_{t0}|$, $\dfrac{d}{|W_{t0}|}$, $\rho_f|W_{t0}|^2$, and $\dfrac{\rho_f|W_{t0}|^2}{d}$ as scaling factors, Eqs. [5] ,[6], and [10] become

$\dfrac{\partial\hat{C}}{\partial\hat{t}} + \dfrac{\partial\hat{C}\hat{u}_j}{\partial\hat{x}_j} = -\dfrac{\partial\hat{C}\hat{W}_{t0}}{\partial\hat{z}} + \dfrac{\partial}{\partial\hat{x}_j}\left(\hat{D}\dfrac{\partial\hat{C}}{\partial\hat{x}_j}\right)$ [20]; $\dfrac{\partial\hat{\rho}}{\partial\hat{t}} + \dfrac{\partial\hat{\rho}\hat{u}_j}{\partial\hat{x}_j} = 0$ [21], and

$\dfrac{\partial\hat{\rho}\hat{u}_i}{\partial\hat{t}} + \dfrac{\partial\hat{\rho}\hat{u}_i\hat{u}_j}{\partial\hat{x}_j} = -\dfrac{\partial\hat{P}}{\partial\hat{x}_i} + \dfrac{1}{\mathrm{Re}_p}\dfrac{\partial\hat{\tau}_{ji}}{\partial\hat{x}_j} + \hat{F}\delta_{i1} + Ri\delta_{i3}$ [22], where ^ indicates a non-dimensional variable, with $\hat{D} = \beta(C)\left|\dfrac{\partial\hat{u}_j}{\partial\hat{x}_i}\right|$ [23], and $Ri = \dfrac{(1-\hat{\rho})dg}{|W_{t0}|^2}$.

RESULTS

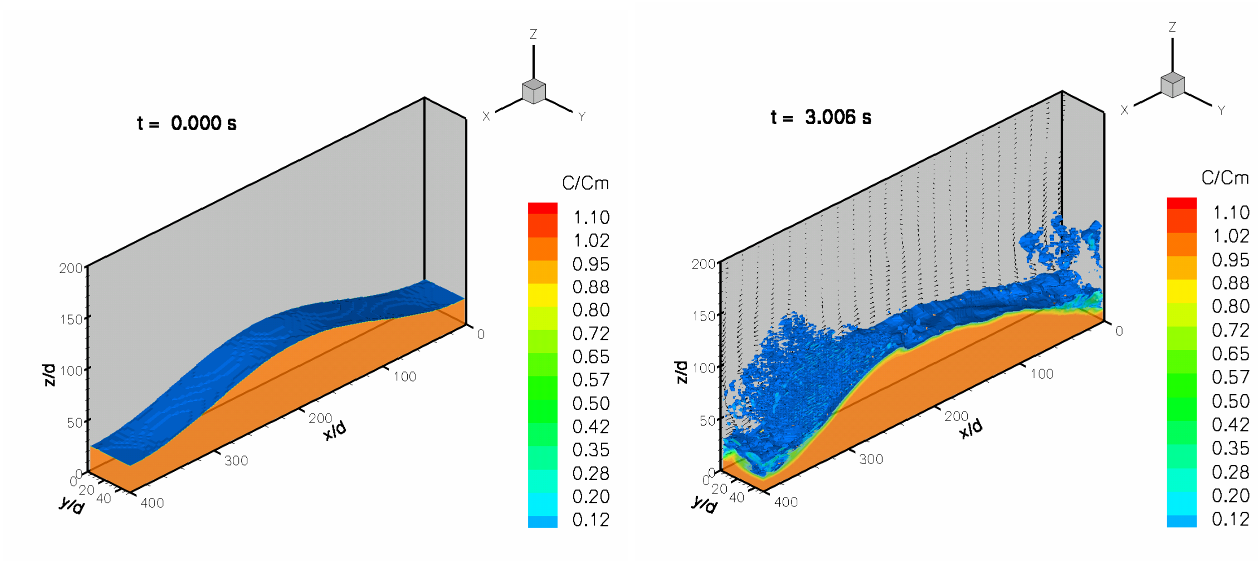

Figure 1. Concentration field of sand (color contours) and velocity vectors of the initialized sand ripple (left panel) and during flow reversal (right panel) showing sediment suspension and changes in the bedform after 1.5 wave periods. For this case the ripple length is 16 cm and the maximum wave orbital velocity is 30 cm/s.

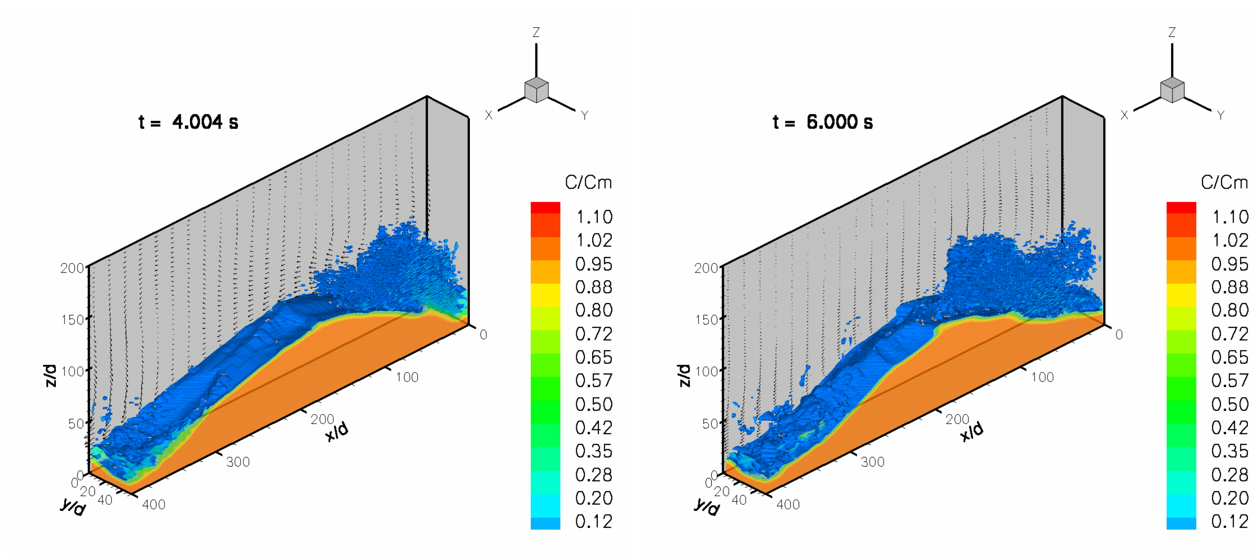

Figure 2. Concentration field of sand (color contours) and velocity vectors of the evolving sand ripple at t = 4.0 and 6.0 seconds. The sand ripple becomes more steep crested and eventually equilibrates with an amplitude of 2.6 cm from crest to trough.

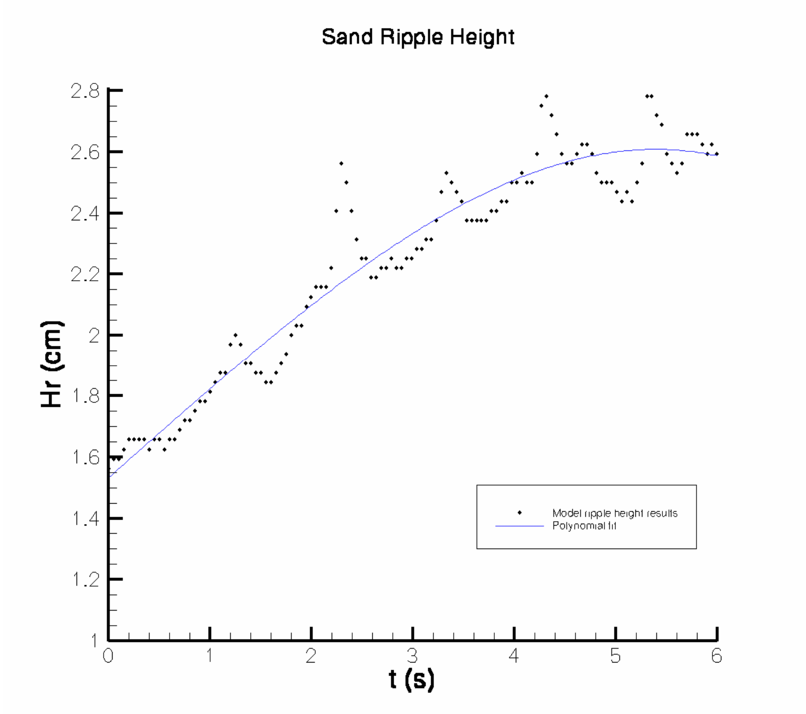

Figure 3. Time evolution of sand ripple height, defined as the difference in the vertical location of the packed bed at it's minimum in the trough and at it's maximum at the crest, calculated from where the sand concentration exceeds 95% of it's fully packed value.

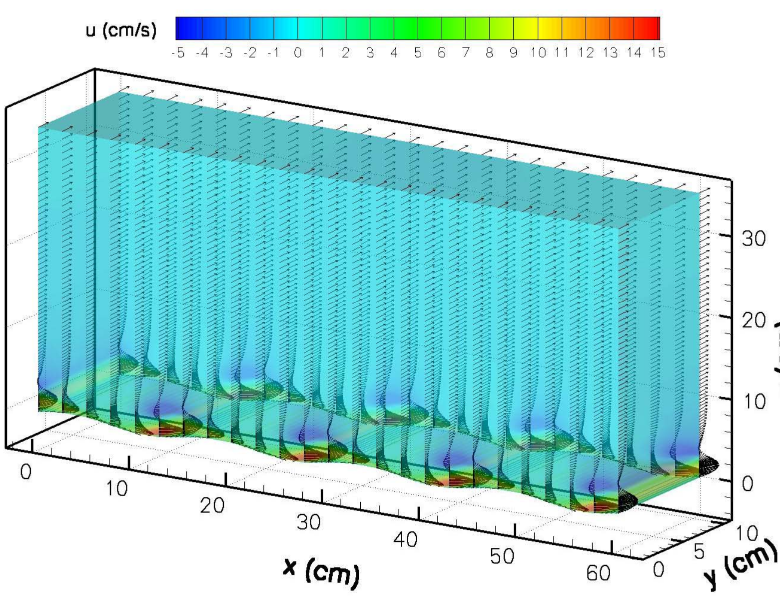

Figure 4. Flow field calculated using the second modeling approac, where the bed is updated based on standard bed-load and suspended load formulations for combined wave and current flow. Here the mean flow is perpendicular to the orientation of the sand ripples.

Simulations of coupled sand ripple and hydrodynamic response to wave driven currents have shown that stable sand ripples can develop after a few wave periods (Figures 1-3). The two-phase mixture approach, modified to include a rigid particle pressure force in the regime of enduring grain-to-grain contact has been successful at producing results qualitatively and quantitatively similar to those observed in laboratory experiments. A set of (150) experiments has been conducted to determine the best formulation for the particle-pressure force as a function of concentration across the sediment – water interface. High resolution three-dimensional simulations take approximately 1 month to complete approximately 15 wave periods of simulation time. We are currently working on implementing the code on a parallel computing environment. The mixture approach appears to have great promise. It has limitations, however, for example, it is presently only capable of simulating domains on the order of 20 cm x 10 cm x 10 cm on a side, given our computing environment. We have developed a second model for simulating larger domains, potentially capable of simulating domains on the order of 1 meter cubed (500 times larger domain than the mixture approach).

The second modeling approach, implements the Meyer-Peter power law formulation and the Bagnold-Bailard-Inman (1981) bed-load and suspended load formulas and updates the bed position by integrating the divergence of the sediment flux through a sediment continuity equation: $\frac{\partial h}{\partial t}+\frac{\partial Q_x}{\partial x}+\frac{\partial Q_y}{\partial y}=0$. This model has also been coded and is in the testing phase. Present results suggest that the bulk formulas for Q are not readily adaptable for localized scour rates in the sand ripple regime. Figure 4 shows a flow field developing about an initialized sand ripple bed.

IMPACT/APPLICATIONS

Our models represent very new approaches. If they can be shown to predict sediment transport and ripple formation accurately significant new tools for understanding the dynamics of small scale sediment transort will be available.

RELATED PROJECTS

The ONR Sand Ripple DRI project has several related ongoing projects.

PUBLICATIONS

None yet.

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